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State of the knowledge on water resources and natural hazards under climate change in Central Asia and South Caucasus

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Thematic Input Paper 1

State of the knowledge on water resources and natural hazards under climate change in Central Asia and South Caucasus

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1. Background/Scope

Climate change is expected to have profound impacts on water resources and natural hazards in Central Asia and South Caucasus. It is critical that we understand such impacts, particularly in the context of rapid socio-economic change that will have implications for the vulnerability of populations in the region. This paper aims to provide a synthesis of the scientific evidence of these changes, their magnitudes and expected consequences. These two distinct regions have extremely heterogeneous climates controlled by elevation and latitude and by location on the continent. Given the large spatial extent of the regions, local climates are highly variable.

The paper starts from an analysis of observed and projected changes in term of the atmospheric drivers of change, e.g. air temperature and precipitation anomalies at the global and regional level. Observed climate change refers to measurements taken at individual stations, satellite data and data obtained from assimilated meteorological data (reanalysis data). Climate projections are obtained by using quantitative methods to simulate the response of the main earth's system components (air, land, oceans, cryosphere) to an increase in greenhouse gas (GHG) concentrations. Climate scenarios to simulate future GHG concentrations are given by the Representative Concentration Pathways (RCPs). In this paper we will refer to results for the RCP2.6 and RCP8.5 scenarios. RCP2.6 represents a mitigation scenario aiming at keeping the level of global mean temperature increase to 2 °C above the pre-industrial level, whereas RCP8.5 represents a scenario of business as usual with an expected average temperature increase to 4 °C above the pre-industrial level. We then assess the state of knowledge on climate change impacts on water resources, weather extremes and mass movements. We discuss implications of climate change for the management of water resources and natural hazards through a risk perspective. We synthesise knowledge from peer review literature and to a certain extent key literature of international organisations. We have used available datasets to generate new graphs on climate and glacier changes in the region. The reviewed literature is necessarily biased towards Central Asia due to considerably less literature being available for the South Caucasus region.

2. Regional profiles

Central Asia consists of the former Soviet republics of Kazakhstan, Kyrgyzstan, Tajikistan, Turkmenistan and Uzbekistan. Central Asia covers an area of 4 million square kilometres and has a population of 60 million people and a population density of just 15 people/km^2. It has a varied topography characterised by vast deserts, grassy steppes and high, glaciated mountain ranges. Mountains cover approximately 20% of the area, with Tajikistan and Kyrgyzstan being the most mountainous countries (>90% of their territories). Major mountain ranges are the Tien Shan and the Pamir-Alai. The Tien Shan mountain range spans from Uzbekistan to Kyrgyzstan, and in the south-east from Kazakhstan to China (Xinjiang). Major river systems of the region include the Amu Darya and the Syr Darya. Major water bodies are the Aral Sea, Lake Balkhash and Issyk Kul Lake, which are part of the west-central Asia endorheic basin that also includes the Caspian Sea (Figure 1).

The climate of the region is extremely heterogeneous and strongly controlled by latitude, altitude and location on the continent. Mean annual air temperatures (MAATs) are around +5 °C in northern Kazakhstan to +20 °C in southern Uzbekistan, whereas MAAT is strongly sub-zero in many parts of the Tien Shan and Pamir (Figure 3A). Precipitation is controlled by the same factors, with arid interior regions of Uzbekistan and Turkmenistan (200mm) whereas northern parts of Kazakhstan are more humid (600–700mm).

Figure 1: Water Resources in Central Asia

Precipitation hotspots of up to 2,000mm can be found in the Tien Shan and Pamir mountains whereas regions to the east of the main ranges and bordering China are more arid (Figure 3A).

South Caucasus consists of the former Soviet states of Armenia, Azerbaijan and Georgia, and sits between the Black Sea (west) and Caspian Sea (east). The Caucasus area of 186,100km^2 is home to a population of 16 million people. The Caucasus Mountains are the divide between Europe and Asia and greatly influence the climate of the region. The region shows a marked topography within a very narrow distance. The highest point is Mount Shkhara at 5,201m, and the lowest point is -28m. The climate is extremely diverse varying with both longitude and altitude. The Great Caucasus range protects the region from the direct penetration of cold air masses from the north and strongly dictates the precipitation rates. Precipitation decreases from west to east and generally mountain areas receive more precipitation than low-lying areas. The region shows an extreme precipitation gradient west to east with 2,393mm/year in Batumi (humid subtropical) and 258mm/year in Baku (cold semi-arid), while mean annual air temperatures are quite similar at 14.2 °C and 15.1 °C, respectively. The largest rivers are the Mtkvari, the Kura and the Araks, with lengths of 1,564, 1,515 and 1,072 kilometres, respectively (Figure 2).

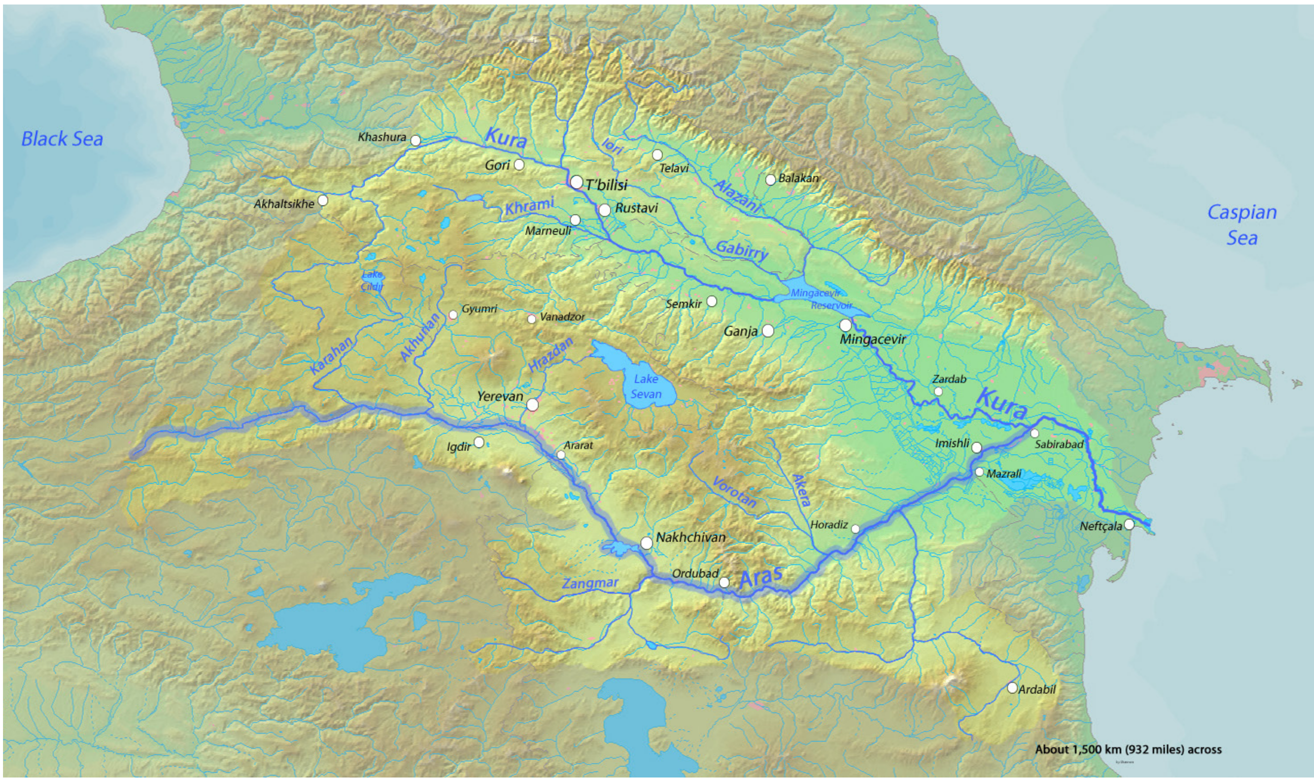

Figure 2: Hydrographic map of Caucasus

Source: Shannon/Wikimedia Commons, http://www.glimpsefromtheglobe.com/topics/politics-and-governance/forecasting-water-wars-in-the-caucasus/

3. State of knowledge

3.1. Observed climate change

Mean annual air temperature has increased over the past century over most of the South Caucasus and Central Asia regions. The numbers of cold days and nights have decreased and the numbers of warm days and nights have increased across most of Asia since about 1950, and heatwave frequency has increased since the middle of the 20th century in large parts of Asia (Hijioka et al. 2014).

In line with observed northern hemisphere warming, large trends (>2 °C per 50 years) in the second half of the 20th century were observed in the northern Asian sector (Hijioka et al. 2014). Most studies focusing on Central Asia mountain regions also document mean-annual (Hijioka et al. 2014) and summertime (e.g., Shahgedanova et al. 2010) warming, with slight cooling in the central and eastern Pamir (Aizen 2011b), which is shown in Figure 3B. The warming trend in mean annual air temperature appears to be less pronounced at high altitudes than in the lower elevation plains and protected intramontane valleys (Unger-Shayesteh et al. 2013). For the winter months, however, a stronger warming trend can be detected at higher elevations of the Tien Shan Mountains (Kriegel et al. 2013; Mannig et al. 2013; Zhang et al. 2009).

Precipitation trends, including extremes, are characterised by strong variability, with both increasing and decreasing trends observed in different parts of the region. In southern Central Asia, a weak downward trend in mean precipitation was observed in recent decades, although with an increase in intense weather events (IPCC AR5, Figure 3B). In mountain regions, precipitation increases have been detected (e.g., Braun et al. 2009; Glazyrin and Tadzhibaeva 2011).

Reanalysis data from the European Centre for Medium-Range Weather Forecasts (ERA-Interim[1]) shows widespread warming across the region (Figure 3B). Localised cooling is seen in locations such as the Pamir (in agreement with Aizen 2011). Precipitation anomalies show general drying trends in the west of the region around the Caspian Sea and Caucasus and in western China. Very localised wet anomalies can be seen in north-east Kazakhstan (in agreement with projected changes).

1. https://www.ecmwf.int/en/forecasts/datasets/archive-datasets/reanalysis-datasets/era-interim

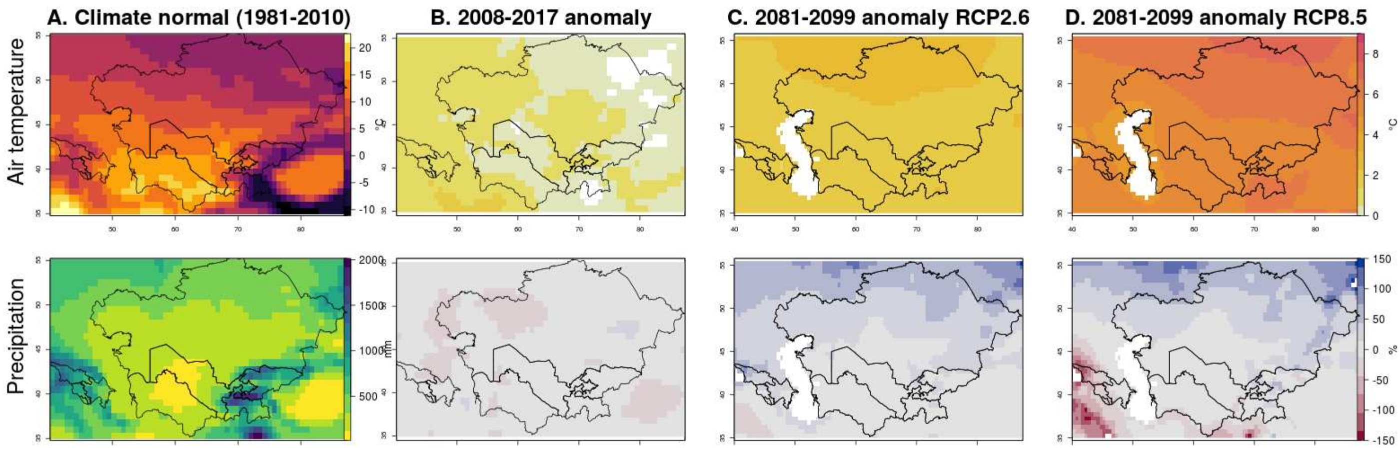

Figure 3: Observed and projected climate change in Caucasus and Central Asia as reported by ERA-Interim reanalysis for climate normals[5] (A) and current anomaly (B) and GCM multi-model means (Hempel et al. 2013) for RCP2.6 (C) and RCP8.5 (D) (projected changes 2081–2099). Cooling of up to 1 °C is shown in white in panel (B). Note all temperature scales are in °C, precipitation normal is in mm whereas precipitation anomalies are in % change.

3.2. Projected climate change

Warming across the Central Asia land area is projected to be higher than the global mean. The multi-model mean[2] summer warming for 2071–2099 is about 2.5–6.5 °C above 1951–1980, in a 2–4 °C world (Reyer et al. 2017, Figure 3). In line with the broad IPCC findings,[3] results from the ISIMIP[4] project (Figure 3) show widespread warming of 2–3 °C in RCP2.6, with a latitudinal trend. In RCP8.5 warming is much more intense at 6–8 °C and additional warming hotspots over the high altitude regions of the Pamir and Southern Tien Shan.

Projected future changes in annual precipitation exhibit a south-west to north-east dipole pattern, with regions in the south-west becoming drier and regions in the north-east becoming wetter (Figure 3D). The "dry-getting-drier and wet-getting-wetter" under climate change is a good first order approximation for the region. Increased wetness in the north-east is the most pronounced signal, in agreement with the strong global precipitation increases projected for high latitude regions in winters. The increase/decrease in precipitation is far more pronounced during the winter (DJF) than during summer (JJA) (Mannig et al. 2013). The multi-model mean drying signal in the south-west, including the Caucasus region, is very weak (almost flat) under low-emissions scenarios (2 °C world), and the models disagree about the direction of change. There is robust model agreement, however, that under the high-emissions scenario (4 °C world), the Caucasus region, Turkmenistan and Uzbekistan will receive less rain, with the multi-model mean annual precipitation dropping by about 20%.

3.3. Changing water towers

High mountain areas of the world are often referred to as "water towers" due to their critical role in supplying lowland regions with water. This is especially true for the large irrigated regions of both Central Asia and Caucasus. Here, seasonal storage of freshwater as snow and inter-annual storage as glacier ice provides a critical water reserve that supplies agricultural and domestic water during dry summer seasons, and replenishes groundwater reserves. Therefore, understanding projected changes in high mountain water resources is critical, particularly in the regions that have seasonal precipitation regimes (southern Central Asia).

Glaciers: Clear evidence from observations shows that glaciers are retreating throughout Central Asia (WGMS 2018) and Caucasus (WGMS 2018; Tielzide 2016; Bondyrev et al. 2015; Shahgedanova et al. 2005) as a response to rising global air temperatures (Figure 4). Where multiple surveys are available, most show accelerating loss. Rates between -0.05% yr^{-1} and -0.76% yr^{-1} have been reported in the Altai (Surazakov et al. 2007; Shahgedanova et al. 2010) and Tien Shan (Lettenmaier et al. 2009; Sorg et al. 2012), and between -0.13% yr^{-1} and -0.30% yr^{-1} in the Pamir (Konovalov

2. Results from multiple models are averaged to account for uncertainties related to different modelling schemes.
3. WG1AR5: Annex I: Atlas of Global and Regional Climate Projections (http://www.ipcc.ch/pdf/assessment-report/ar5/wg1/WG1AR5_AnnexI_FINAL.pdf)
4. A community driven modelling effort to provide cross-sectoral impacts of climate change based on the RCP scenarios www.isimip.org
5. Climate is commonly described using the long-term averages of meteorological parameters (such as temperature, precipitation and hours of sunshine), as well as the differences from these averages. The 30-year average and 30-year averaging period are used as standard for climate normals worldwide.

and Desinov 2007; Aizen 2011). Tielzide (2016) found that the area of Georgian glaciers declined by 42.0 ± 2.0% between 1911 and 2014, with highest retreat rate seen in the eastern region (67.3 ± 2.0%). These ranges reflect varying sub-regional distributions of glacier size (smaller glaciers shrink faster) and debris cover (which slows shrinkage), but also varying proportions of ice at high altitudes, where as yet warming has produced little increase in melt (Narama et al. 2010). Marzeion et al. (2012) found 21st century volume losses could be 50% for RCP2.6, and 67% for RCP8.5. The concept of peak water (Huss and Hock 2018 and references therein) is important in understanding glacial contributions to surface run-off. As melt rates increase, run-off will also increase until a certain tipping point when the glacial mass is reduced to such an extent that run-off starts to decline. The study of Huss and Hock (2018) found that for the basins of the Aral Sea this point is approximately mid-century. For Caucasus this point is now and glacial discharge is likely decreasing over widespread areas (Huss & Hock 2018). In addition, the Amu Darya will likely see greater losses compared to the Syr Darya or Naryn in Central Asia due to its higher glaciated area (World Bank 2015). More immediately, glacial retreat creates a hazard due to the formation of moraine-dammed glacial lakes with the possibility of outburst floods (GLOFs) (Bolch et al. 2011; Kapitsa et al. 2017).

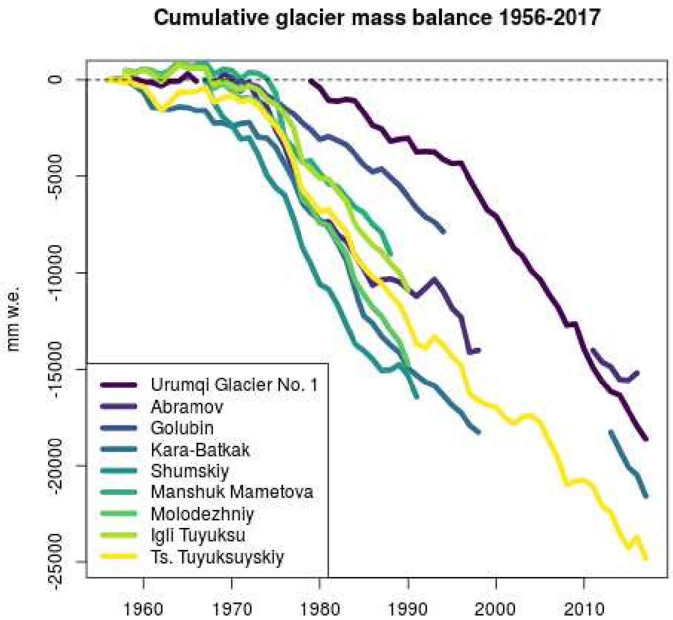

Figure 4: Changes in mass balance of Central Asian glaciers over the past half century
(credit: WGMS)

Seasonal snow cover: Over large parts of southern Central Asia seasonal snow cover contributes significantly to the annual water budget because precipitation is seasonal and falls mainly during autumn to spring, largely as snow in mountain regions. Reductions in seasonal snow cover are expected to accompany observed warming in the mountains of Central Asia and Caucasus as a higher proportion of winter PR falls as rain (Lemke et al. 2007). Zhou et al. (2017) found significant decreases in the number of snow-on-ground days throughout the Pamir and Tien Shan in an analysis of trends from 1986 to 2008. Peters et al. (2015) found that snow cover changes in the central Tien Shan (1986–2012) show a slight decrease in altitudes up to 4,000m and an opposite trend above that level, but significant gradients were found only at high elevations. Global projections estimate an increase in the snow line of around 150m per 1 °C warming (Christensen et al. 2007). Expected changes in seasonality of snow melt will result in earlier run-off and reduced water availability in summer/late summer (Barnett et al. 2005) when demand in the large irrigated zones of Central Asia is highest, particularly in unregulated catchments. Changes in seasonal snow cover are projected to enhance warming in mountain regions through snow-albedo effects (Christensen et al. 2007). In the Amu Darya basin, studies have found that increasing glacial run-off will buffer decreasing snowpack until mid-century when peak water is expected in many areas (Huss & Hock 2017, Figure 3). The second half of the century, however, will then see decreasing run-off as both snow and glacial components decline.

3.4. Extreme weather events

The effects of climate change are projected to cause shifts in present day climate into new regimes, where what we consider to be extreme events today will be increasingly common in the future.

Heat Extremes: Reyer et al. (2017) found that threshold-exceeding heat extremes strongly increase in southern regions in a 4 °C world with respect to the reference period 1951–1980. Heat extremes can be quantified as 3- and 5-sigma events (considering that monthly temperatures are close to a normal distribution, 3- and 5-sigma events represent 3 and 5 standard deviations over the mean temperature, respectively). In a region from eastern Caucasus to central China they found 80% of summer months to exceed 3-sigma events and 40% to exceed 5-sigma events. To put this in context, air temperatures experienced during the warmest 10% of summer nights during the 1961–1990 period are expected to occur in about 30% (2 ˚C world) or 90% (4 ˚C world) of summer nights by the end of the century in regions approximately below 50° latitude (Sillmann et al. 2013). This will likely increase heat stress considerably in human populations, livestock and agricultural crops as well as enhance drought impacts.

Precipitation Extremes: No clear trend in precipitation extremes can be found in the observation record (Dai 2013; Donat et al. 2013), but a moderate drought risk is projected until the end of the century with a 10% decrease in soil moisture in southerly regions of Central Asia and Caucasus.

Although Sillmann et al. (2013) found no significant change in the index "consecutive drought days" in their study Central Asia model domain (includes Caucasus), changes in soil moisture in northern Central Asia are likely to be slightly positive, but warming will have a large influence on soil moisture due to enhanced evapotranspiration. Reyer et al. (2017) found significant increases in land area classified as both arid (19.6, 11.6) and hyper arid (22.4, 14.4) in both 2 °C and 4 °C worlds. Specifically, under a 4 °C world significant increases in aridity in already drought-prone regions such as southern Kazakhstan, Uzbekistan and Turkmenistan can be expected, with serious implications for agriculture and food security. Although drought projections remain uncertain, at least in the precipitation signal, regional water availability will be strongly affected by changes in river run-off due to glacier melting and changes in seasonal snow storage (next section). Atmospheric warming speeds up the hydrological cycle and is expected to increase the frequency of intense precipitation events throughout the region (Sillmann et al. 2013). Mountainous regions of Central Asia are very prone to the flash flooding that can occur after intense precipitation events particularly in steep rocky catchments with narrow canyon outlets. There are many well-documented cases of entire villages being destroyed by this type of event such as the seven-lakes event in 1992 in the Fan mountains in Tajikistan.

3.5. Mass movements

Mass movements are complex phenomena with possible climate triggers e.g. glacier lake outburst floods, debris flows, rock fall and ice or snow avalanches. In general warming in high mountain regions can lead to destabilisation of steep slopes due to loss of mechanical strength e.g. permafrost debris or rock slopes. While climate induced permafrost degradation (observed at GTNP[6] sites in Tien Shan e.g. Marchenko et al. 2007) can be a key driver of such events, disentangling the climate signal from normal erosional processes in mountain areas is not straightforward. There is, however, increasing evidence that increased incidence of thermally induced slope instabilities should be expected as high mountain regions warm. A second class of more mechanical mass wasting is debutressing due to glacial retreat that leaves over-steep slopes eroded by the former glacier flow. These slopes are inherently unstable and prone to collapse. Snow avalanches are significant hazards in both Central Asia and Caucasus and can threaten exposed infrastructure and settlements. The impact of climate change on snow avalanches is complex and uncertain. Reduced average snowpack depths would serve to reduce frequency of large events. There is some evidence of large precipitation events in winter becoming more frequent. Such events would promote large avalanches even with a background of lower average snow depths. Mass movements often result in compound events, which can impact distant low-lying regions (Mergelli et al. 2018). Compound events are usually associated with different interacting physical processes over multiple temporal and spatial scales (Zscheischleret al. 2018), e.g. a glacier lake outburst flood triggered by an impact wave from an ice avalanche upstream, in turn triggering a debris flow with entrainment of material. Earthquakes can often be the trigger of such compound processes and while not coupled to climate can trigger mass movements on slopes destabilised by warming.

Box 1: Compound events on Mount Kazbek Massif, Caucasus

On 17 May 2014 an ice avalanche released from the Devdoraki Glacier on Mt. Kazbek (5,033m) in Georgia. The ice avalanche triggered a massive mud and debris flow. The flow travelled downstream to the Tergi River, which was temporarily blocked and gave rise to a 20–30m deep lake with a water volume of 150,000m^3. The debris covered a highway of international importance between Georgia and Russia, and an international gas pipeline and the building site of a new hydropower plant were damaged. The disaster claimed the lives of nine people and created disruption in the downstream communities (Tielidze 2017). This is the same region where in September 2002 a hanging glacier released ice and rock onto the Kolka glacier triggering a massive avalanche of ice, snow and rocks into the river in the valley. The avalanche swallowed the village below and several other settlements.

6. Global Terrestrial Network for Permafrost mandated by Global Climate Observing System/WMO

4. Knowledge gaps and challenges

4.1. Models

Climate projections simulate the response of the climate system to a scenario of future greenhouse gas emissions and are derived using climate models. Climate models can be understood as numerical representations of the climate system based on biological, chemical and physical properties of the atmosphere, cryosphere, land and ocean components including their interactions and feedback. The most advanced climate models are General Circulation Models (GCMs), with a spatial resolution of 100–300km, as used by the IPCC and the literature in this review to assess climate change at the global scale. Coarse resolution means that topographic features even as large as the Pamir Tien Shan are not well resolved and therefore surface processes are not well represented leading to generally greater uncertainties in mountain regions as compared to low-lying regions. Our projections may also be informed by observations in the case of debiasing, which is also problematic in mountain regions where observations are sparse and not representative of larger regions. Regional Climate Models can address the resolution problem to some extent by downscaling but are still prone to uncertainties related to surface process representations.

4.2. Observations and networks

In situ measurements and monitoring of glaciers, snow and permafrost constitute the data basis for ascertaining and processing changes in upstream and downstream systems due to climate change. Thus, long-term and continuous in situ observations and measurements are of paramount importance in addressing climate change impacts on water resources and natural hazards. Continuous in situ measurements and monitoring in remote areas such as the mountain areas of Central Asia and Caucasus are challenging tasks due to the difficult access, complex topography, financial and logistic constraints, political instability and lack of appropriate infrastructure (Hoelzle et al. 2017). Several studies have reported the lack of appropriate and reliable datasets as one of the most important constraints to understanding patterns of changes in Central Asia (Unger-Shayesteh et al. 2013; Hoelzle et al. 2017). Most areas of the Asian region lack sufficient observational records to draw conclusions about trends in annual PR over the past century (Hijioka et al. 2013; Figure 24-2; Table SM24-2). If weather stations are present at all, they are usually located at lower elevations where most of the population lives. There are very few datasets above 3,000m and virtually none above 5,000m. Remote sensing data as well as model-assimilated observations (from reanalysis data) are used to fill the observational gap. Their products are becoming increasingly popular and show increased skill. The relatively short time series and coarse resolution, however, do not allow for robust assessments of changes in mountain areas, where the complex topography requires finer resolutions (< 5km) (Prein et al. 2015). This makes the need for denser observational networks in remote mountain areas ever more urgent.

Management of extreme events and mass movements requires monitoring, recording and reporting of events over relatively long timescales and standardised data reporting. In locations where resources are scarce and funds are limited, this is often not a priority. Permafrost monitoring is also very important for understanding slope stability and the influence of permafrost on water resources. Permafrost monitoring is patchy in the regions with only five permafrost boreholes in Central Asia (all with discontinuous measurements) and none in Caucasus (Biskaborn et al. 2015). Considerable work has been undertaken since the 1990s to address these gaps. Steps include re-establishing monitoring sites and building capacities and innovations through international projects such as Central Asia Water,[7] an international consortium of German and Central Asia institutions, the Capacity Building and Twinning Climate Observing System of the Swiss Agency for Development and Cooperation,[8] the Water Management in the South Caucasus project of the United States Agency for International Development, and the Central Asia Hydrometeorology Modernization Project[9] of the World Bank.

7. http://cawater-info.net/
8. https://www.meteoschweiz.admin.ch/home/forschung-und-zusammenarbeit/projekte.subpage.html/de/data/projects/2011/catcos.html
9. http://projects.worldbank.org/P120788/central-asia-hydrometeorology-modernization-project?lang=en

5. Implications for water and disaster risk management

5.1 The risk perspective: Hazard, exposure and vulnerability

The IPCC risk framework in the background of Figure 5 (IPCC 2012, 2014) provides a useful approach for discerning the different drivers of climate risks for a country or a region. It recognises that climate impacts and risks emerge from the complex interplay of multiple factors, not least the past and current pathways of socio-economic and political development. This perspective is useful for addressing current and future management issues since it distinguishes the physical causes of risks (hazards as discussed in the previous section) from causes related to exposure (number of people, infrastructure) and past and present pathways of development (vulnerability) (Allen et al. 2018). In this section we look at the risks associated with changes in water resources and changes in the natural disaster landscape as a consequence of climate change, and highlight the contributions of exposure and vulnerability to climate-related risks (Figure 5).

5.2 Water availability and management

Due to the semi-arid to arid climate, Central Asia and part of South Caucasus are heavily dependent on fresh water supplies from snow and glacier melt for irrigation, hydropower and domestic use. Changes in timing (seasonality) and amounts of fresh water can have serious implications for the future management of irrigated agriculture and energy generation from hydropower. This effect will be most strongly felt in the large irrigation zones of Central Asia, but also in potential upstream hydroelectric schemes such as the Nurek dam in Tajikistan. Mankin et al. (2015) conducted a global study of sensitivity of individual basins to changes in snow supply under climate change projections. They found that currently the basins of Central Asia significantly depend on snow melt to serve summer demand (demand refers to surface and subsurface water consumption from agricultural, industrial and domestic use), whereas Caucasus rainfall is sufficient to meet demand. In addition, they found a high risk that snow melt will no longer meet summer demand by mid-century in central Asian basins. They also found evidence for a shift from sufficient to insufficient rainfall run-off to meet water demand in the Caucasus region by 2080.

Given the already very high level of water stress in many parts of Central Asia, observed and projected air temperature increases and precipitation decreases in the western part of Kazakhstan, Uzbekistan and Turkmenistan (Figure 3) could exacerbate the problems of water shortage and distribution (Lioubimtseva and Henebry 2009). Considering the dependence of Uzbekistan's economy on its irrigated agriculture, which consumes more than 90% of the available water resources of the Amu Darya basin, climate change impacts on river flows would also strongly affect the economy (Schlüter et al. 2010).

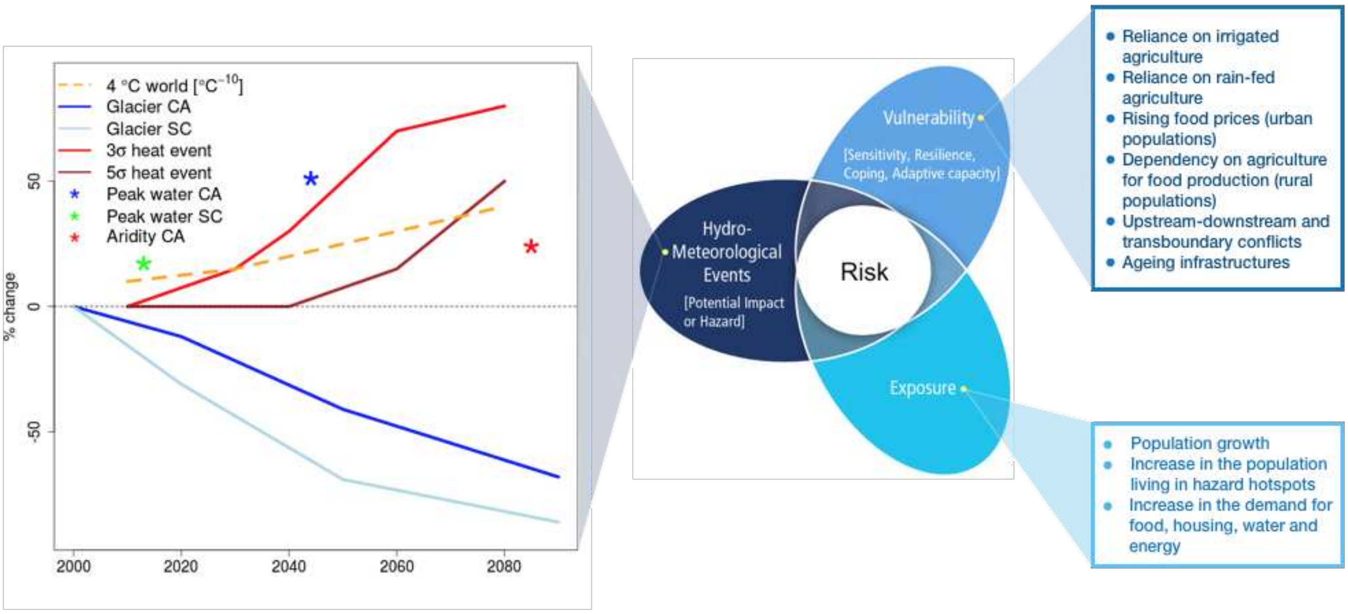

Figure 5: The risk concept adapted from the IPCC (2012, 2014) highlights the interactions between hazard, exposure and vulnerability as components of risk. The hazard box (left side) synthesises the main trends from current observations and projections until the second half of the century as reported in this paper. The right side summarises main elements of current vulnerability and exposure common to both regions as collected from the reviewed literature.

Recent studies have demonstrated that the risk of water scarcity in the region is strongly associated with high water demand driven by socio-economic pressure and demographic trends (increased exposure) (Luck et al. 2015). In Central Asia, inefficient water usage for irrigation and degradation of croplands has already resulted in a 30% decline in crop productivity since the 1990s (Conrad et al. 2013). Depending on the climate scenarios, agriculture productivity might decline by as much as 20–50% by 2050 (compared to a 2000–2009 baseline) in Uzbekistan and up to 30% in Tajikistan if appropriate adaptation measures are not implemented (Reyers et al. 2017). Loss of agricultural productivity combined with soaring population and food prices can have direct impacts on food security for large sections of the population. In the already water stressed and drought-prone areas of the Ararat valley in Armenia, climate change is expected to lead to enhanced TA and reduced PR resulting in more frequent drought conditions. Furthermore, an expected reduction in the flow of a major river (Arpy River) and a decrease in groundwater levels will pose serious challenge for a country dependent on agriculture for more than 20% of its GDP (Melkonyan 2015). In parts of Azerbaijan existing water stress due to inefficient use, unequal distribution and seasonal fluctuations are already causing major concerns. Improved water use efficiency in irrigation, changing or rotating crop systems and water reuse might ease water stress and improve agriculture productivity (Aleksandrova et al. 2014).

5.3 Management of upstream-downstream hazards

The presence of a marked downstream–upstream topography renders the two regions particularly prone to gravitational hazards such as landslides, debris flows, mudflows, ice, snow or rock avalanches and GLOFs. While it is still statistically difficult to directly link such events and the frequency of occurrence to shifts in global climate, there is growing evidence from the Alps (Huggel et al. 2012) and a sound physical basis for increased occurrence of mass movements in high mountain regions. As permafrost slopes warm they become less stable and as glaciers recede they leave behind inherently unstable slopes that have become overly steepened, and large amounts of sediments that can be mobilised in large destructive debris flows. The sequence of processes leading to these types of hazards needs to be reasonably well understood to devise appropriate adaptation and disaster risk reduction strategies. Several other contributing effects or confounders play a role in the dynamics of disasters generated by gravitational hazards, such as the increased number of people and assets in hotspot areas (exposure) as well as lack of appropriate risk preparedness and information (vulnerability). It is thus of paramount importance to intensify the development of soft, no-regrets adaptation measures that are flexible and robust and that allow for adaptive management (Hallegatte 2009), hazard, exposure and vulnerability mapping, capacity building and training, and Early Warning Systems.

Box 2: Transboundary processes and management challenges

The Syr Darya River basin originates in the Tian Shan Mountains in Kyrgyzstan, flows across Tajikistan, Uzbekistan and Kazakhstan, and ends at the Aral Sea. During the Soviet era extensive irrigation in the downstream countries of Uzbekistan and Kazakhstan was developed. Upstream countries provided water for spring and summer irrigation to the downstream countries and received fossil fuel in exchange. After the breakup of the Soviet Union, Kyrgyzstan, which is poor in fossil fuels, started storing water in spring and summer to be used in the fall and winter for hydropower generation. The downstream countries, however, still need large amount of water during April-September for irrigation. Projections show that for the Aral Sea basin peak water could be reached in 2030±5 (RCP2.6) and 2044±15 (RCP8.5) followed by a steady decline in glacier run-off (Huss & Hock 2018). The impacts of glacier melting and reduced snow cover will be felt both upstream and downstream. Additionally, studies on cooperation regimes indicate that Central Asia has a moderate to high risk of conflicts due to reduced water availability (Bocchiola et al. 2017). The major challenge for the region is thus to manage the diverging needs of the upstream and downstream countries through appropriate transboundary cooperation. To facilitate transboundary cooperation, dynamics of water flows and management need to be well understood to devise appropriate adaptation solutions for the region (Bocchiola et al. 2017). Furthermore, the establishment of the Interstate Commission for Water Coordination of Central Asia[10] located in Tashkent shows a willingness to address current and future challenges in water resource management in the region.

10. http://www.icwc-aral.uz/

6. Key messages

- Climate change is well underway in both regions, positive air temperature anomalies are observed throughout both regions and drying trends are seen in the western regions of Central Asia and Caucasus. Warming is projected to continue throughout the region and, depending on scenario, ranges from a "manageable" 2–3 °C to a dangerous 5–8 °C. Particular hotspots of air temperature increases are northern regions of Kazakhstan and Pamirs and southern Tian Shan.
- Drying trends are likely in south-western parts of Uzbekistan and Turkmenistan and Caucasus, increasing the risk of more frequent and longer periods of drought.
- Caucasus will likely no longer rely on sufficient rainfall to meet summer demand by late century with increased dependence on depleted snow and glacier meltwater resources.
- Significant increases in heat stress in human populations, livestock and crops are very likely throughout both regions during summer months.
- Glaciers are retreating in both regions and will continue to retreat over this century. Peak water has likely already been reached in Caucasus and will be reached by mid-century in Central Asia. Glacial water resources will decrease after this tipping point. The risk of glacial lake outburst flooding is expected to increase.
- Decreasing precipitation, increasing evapotranspiration and reduced run-off from snow and glacial melt will likely combine to severely reduce water resources particularly in irrigated zones of Central Asia in the second half of this century.
- Permafrost mountain slopes throughout both regions will experience thawing during this century over wide areas, increasing the chance of mass movement events such as rockfall, ice avalanches and debris flows. These high mountain events can often travel long distances and affect low-lying communities through complex process chains.
- Lack of adequate monitoring of key environmental variables is a key limitation in understanding past and future trends. Investment in monitoring networks also requires capacity in data management and interpretation as well as maintenance of systems.
- Climate change risks need to be assessed within the specific exposure and vulnerability context of the region in order to devise appropriate adaptation solutions for water and disaster management.

7. References

Aizen, V.B. (2011). Pamirs. In: Encyclopedia of Snow, Ice and Glaciers [Singh, V.P., P. Singh, and U.K. Haritashya (eds.)]. Springer, Dordrecht, Netherlands, pp. 813- 815.

Aleksandrova, M., Lamers, J. P. A., Martius, C., Tischbein, B. (2014). Rural vulnerability to environmental change in the irrigated lowlands of Central Asia and options for policy-makers: A review. *Environmental Science & Policy*, 41, 77–88. https://doi.org/10.1016/j.envsci.2014.03.001

Allen, S. K., Ballesteros-Canovas, J., Randhawa, S. S., Singha, A. K., Huggel, C., Stoffel, M. (2018). Translating the concept of climate risk into an assessment framework to inform adaptation planning: Insights from a pilot study of flood risk in Himachal Pradesh, Northern India. *Environmental Science & Policy,* 87, 1–10. https://doi.org/10.1016/j.envsci.2018.05.013

Barnett, T. P., Adam, J. C., Lettenmaier, D. P. (2005). Potential impacts of a warming climate on water availability in snow-dominated regions. Nature, 438(7066), 303.

Biskaborn, B. K., Lanckman, J., Lantuit, H., Elger, K., Streletskiy, D. A., Cable, W. L. (2015). The new database of the Global Terrestrial Network for Permafrost (GTN-P), 245–259. http://doi.org/10.5194/essd-7-245-2015

Bocchiola, D., Pelosi, M. G., Soncini, A. (2017). Effects of hydrological changes on cooperation in transnational catchments: the case of the Syr Darya. Water International, 42(7), 852–873. http://doi.org/10.1080/02508060.2017.1376568

Bolch, T., Peters, J., Yegorov, A., Pradhan, B., Buchroithner, M., Blagoveshchensky, V. (2011). Identification of potentially dangerous glacial lakes in the northern Tien Shan. Natural Hazards, 59(3), 1691-1714.

Bondyrev, I. V., Davitashvili, Z. V., Singh, V. P. (2015). The geography of Georgia: problems and perspectives. Springer.

Braun, L.N., Hagg, W., Severskiy, I.V., Young, G. (eds.), 2009: Assessment of Snow, Glacier and Water Resources in Asia: Selected Papers from the Workshop in Almaty, Kazakhstan, 2006. IHP/HWRP Report No. 8, the German National Committee for the United Nations Educational, Scientific and Cultural Organization, International Hydrological Programme (UNESCO IHP) and the World Meteorological Organization, Hydrology and Water Resources Programme (WMO HWRP), IHP/HWRP Secretariat, Koblenz, Germany, 183 pp.

Christensen, J. H., Christensen, O. B. (2007). A summary of the PRUDENCE model projections of changes in European climate by the end of this century. Climatic change, 81(1), 7-30.

Conrad, C., Schönbrodt-Stitt, S., Löw, F., Sorokin, D., Paeth, H. (2016). Cropping Intensity in the Aral Sea Basin and Its Dependency from the Runoff Formation 2000–2012. Remote Sensing. http://doi.org/10.3390/rs8080630

Dai, A. (2013). Increasing Drought under Global Warming in Observations and Models. Nature Climate Change, 3(1), 52–58.

Donat, M.G., Alexander, L. V., Yang, H., Durre, I., Vose, R., Dunn, R.J.H., Willett, K.M., Aguilar, E., Brunet, M., Caesar, J.,Hewitson, B., Jack, C., Klein Tank, A.M.G., Kruger, A.C., Marengo, J., Peterson, T.C., Renom, M., Oria Rojas, C., Rusticucci, M., Salinger, J., Elrayah, A.S., Sekele, S.S., Srivastava, A.K., Trewin, B., Villarroel, C., Vincent, L.A., Zhai, P., Zhang, X., and Kitching, S. (2013). Updated Analyses of Temperature and Precipitation Extreme Indices Since the Beginning of the Twentieth Century: The HadEX2 Dataset. Journal of Geophysical Research: Atmospheres, 118(5), 2098–2118.

Glazyrin, G.E., Tadzhibaeva, U.U. (2011). Climate change in the high mountains of Central Asia in the late 20th century. Lëd i Sneg, 114, 12-15 (in Russian)

Hallegatte, S. (2009). Strategies to adapt to an uncertain climate change. Global Environmental Change, 19(2), 240–247. https://doi.org/10.1016/j.gloenvcha.2008.12.003

Hempel, S., Frieler, K., Warszawski, L., Schewe, J., Piontek, F. (2013). A trend-preserving bias correction – the ISI-MIP approach, Earth Syst. Dynam., 4, 219-236, https://doi.org/10.5194/esd-4-219-2013

Hijioka, Y., Lin, E., Pereira, J.J., Corlett, R.T., Cui, X., Insarov, G.E., Lasco, R.D.,Lindgren, E. , Surjan, A. (2014). Asia. In: Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part B: Regional Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Barros, V.R., C.B. Field, D.J. Dokken, M.D. Mastrandrea, K.J. Mach, T.E. Bilir, M. Chatterjee, K.L. Ebi, Y.O. Estrada, R.C. Genova, B. Girma, E.S. Kissel, A.N. Levy, S. MacCracken, P.R. Mastrandrea, and L.L.White (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 1327-1370.

Hoelzle, M., Azisov, E., Barandun, M., Huss, M., Farinotti, D., Gafurov, A., Hagg, W., Kenzhebaev, R., Kronenberg, M., Machguth, H., Merkushkin, A., Moldobekov, B., Petrov, M., Saks, T., Salzmann, N., Schöne, T., Tarasov, Y., Usubaliev, R., Vorogushyn, S., Yakovlev, A., and Zemp, M. (2017). Re-establishing glacier monitoring in Kyrgyzstan and Uzbekistan, Central Asia, Geosci. Instrum. Method. Data Syst., 6, 397-418, https://doi.org/10.5194/gi-6-397-2017

Huggel, C., Allen, S., Deline, P., Fischer, L., Noetzli, J., & Ravanel, L. (2012). Ice thawing, mountains falling—are alpine rock slope failures increasing? Geology Today, 28(3), 98-104.

Huss, M., Hock, R. (2018). Global-scale hydrological response to future glacier mass loss. Nature Climate Change 8 135

IPCC. (2012). Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation. A Special Report of Working Groups I and II of the Intergovernmental Panel on Climate Change [Field, C.B., V. Barros, T.F. Stocker, D. Qin, D.J. Dokken, K.L. Ebi, (eds.)]. Cambridge: Cambridge University Press, Cambridge, UK, and New York, NY, USA. http://doi.org/10.1017/CBO9781139177245

IPCC. (2014). Summary for Policymakers. [Field, C.B., V. R. Barros, D. J. Dokken, K. J. Mach, M. D. Mastrandrea, T. E. Bilir, … L.L.White, (eds.)]: Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change (pp. 1–32). Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA. http://doi.org/10.1017/CBO9781107415324

Kapitsa, V., Shahgedanova, M., Machguth, H., Severskiy, I., & Medeu, A. (2017). Assessment of evolution and risks of glacier lake outbursts in the Djungarskiy Alatau, Central Asia, using Landsat imagery and glacier bed topography modelling. *Natural Hazards and Earth System Sciences*, 17(10), 1837-1856.

Konovalov, V. and Desinov, L. (2007). Remote sensing monitoring of the long-term regime of the Pamirs glaciers. International Association of Hydrological Sciences Publications, 316, 149-156.

Kriegel, D., Mayer, C., Hagg, W., Vorogushyn, S., Duethmann, D., Gafurov, A., Farinotti, D. (2013). Changes in glacierisation, climate and runoff in the second half of the 20th century in the Naryn basin, Central Asia. *Global and Planetary Change, 110*, 51–61. https://doi.org/10.1016/j.gloplacha.2013.05.014.

Lemke, P., Ren, J., Alley, R.B., Allison, I., Carrasco, J., Flato, G., Fujii, Y., Kaser, G., Mote, P., Thomas, R.H. & Zhang, T. (2007). Observations: Changes in snow, ice and frozen ground. In: Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change [Solomon, S., Qin, D., Manning, M., Chen, Z., Marquis, M., Averyt, K.B., Tignor, M. & Miller, H.L., (eds)]. Cambridge University Press, Cambridge, UK, and New York, NY, USA, pp. 337–383

Lettenmaier, D.P., Aizen, V., Amani, A., Bohn, T., Giorgi, F., Harrison, S., Huntington, T.G.,Lawford, R. , Letitre, P. , Lins, H., Magomi, J. , Park, G.-K., Severskiy, I., Shuttleworth, W.J.,, Singh, P., Sorooshian, S., Struckmeier, W., Takeuchi, K., Tallaksen, L., Vörösmarty, C. , Yan, T., Zhang, T. (2009): Changes in the global water cycle. In: The United Nations World Water Development Report 3: Water in a Changing World. Report published on behalf of the World Water Assessment Programme by the United Nations Educational, Scientific and Cultural Organization (UNESCO), Paris, France and Earthscan, London, UK, pp. 181-225.

Lioubimtseva, E., Henebry, G. M. (2009). Climate and environmental change in arid Central Asia: Impacts, vulnerability, and adaptations. *Journal of Arid Environments*, 73(11), 963–977. https://doi.org/10.1016/j.jaridenv.2009.04.022

Luck, M., Landis, M., Gassert, F. (2015). Aqueduct Water Stress Projections: Decadal Projections of Water Supply and Demand Using CMIP5 GCMs. Technical Note. Washington, D.C.: World Resources Institute.

Mankin, J.S., Viviroli, D., Singh, D., Hoekstra, A.Y., Diffenbaugh, N.S. (2015). The potential for snow to supply human water demand in the present and future. Environmental Research Letters, 10(11), 114016. https://doi.org/10.1088/1748-9326/10/11/114016

Mannig, B., Müller, M., Starke, E., Merkenschlager, C., Mao, W., Zhi, X., Podzun, R., Jacob, D, Paeth, H. (2013). Dynamical downscaling of climate change in Central Asia. Global and planetary change, 110, 26-39.

Marchenko, S. S., Gorbunov, A. P., Romanovsky, V. E. (2007). Permafrost warming in the Tien Shan mountains, central Asia. Global and Planetary Change, 56(3-4), 311-327.

Marzeion, B., Jarosch, A.H., Hofer, M. (2012). Past and future sea-level change from the surface mass balance of glaciers. Cryosphere, 6(6), 1295-1322.

Melkonyan, A. (2015). Climate change impact on water resources and crop production in Armenia. Agricultural Water Management, 161, 86–101. https://doi.org/10.1016/j.agwat.2015.07.004

Mergili, M., Emmer, A., Juřicová, A., Cochachin, A., Fischer, J.-T., Huggel, C., Pudasaini, S. P. (2018). How well can we simulate complex hydro-geomorphic process chains? The 2012 multi-lake outburst flood in the Santa Cruz Valley (Cordillera Blanca, Perú). Earth Surf. Process. Landforms, 43: 1373–1389. https://doi.org/10.1002/esp.4318

Narama, C., Kaab, A., Duishonakunov, M., Abdrakhmatov, K. (2010). Spatial variability of recent glacier area changes in the Tien Shan Mountains, Central Asia, using Corona (similar to 1970), Landsat (similar to 2000), and ALOS (similar to 2007) satellite data. Global and Planetary Change, 71(1-2), 42-54

Peters, J., Bolch, T., Gafurov, A., Prechtel, N. (2015). Snow cover distribution in the Aksu catchment (central Tien Shan) 1986–2013 based on AVHRR and MODIS data. IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing, 8(11), 5361-5375.

Prein, A. F., Langhans, W., Fosser, G., Ferrone, A., Ban, N., Goergen, K., Leung, R. (2015). A review on regional convection-permitting climate modeling: Demonstrations, prospects, and challenges. Reviews of Geophysics, 53(2), 323–361. https://doi.org/10.1002/2014RG000475

Reyer, C. P. O., Otto, I. M., Adams, S., Albrecht, T., Baarsch, F., Cartsburg, M., Stagl, J. (2017). Climate change impacts in Central Asia and their implications for development. Regional Environmental Change, 17(6), 1639–1650. http://doi.org/10.1007/s10113-015-0893-z

Schellnhuber, H.J., Reyer, C., Hare, B., Waha, K., Otto, I.M., Serdeczny, O., Schaeffer, M., Schleußner, C.F., Reckien, D., Marcus, R., Kit, O., Eden, A., Adams, S., Aich, V., Albrecht, T., Baarsch, F., Boit, A., Canales Trujillo, N., Cartsburg, M., Coumou, D., Fader, M., Hoff, H., Jobbins, G., Jones, L., Krummenauer, L., Langerwisch, F., Le Masson, V., Ludi, E., Mengel, M., Möhring, J., Mosello, B., Norton, A., Perette, M., Pereznieto, P., Rammig, A., Reinhardt, J., Robinson, A., Rocha, M., Sakschewski, B., Schaphoff, S., Schewe, J., Stagl, J., Thonicke, K. (2014). Turn down the heat: confronting the new climate normal. The World Bank, Washington DC

Schlüter, M., Hirsch, D., Pahl-Wostl, C. (2010). Coping with change: responses of the Uzbek water management regime to socio-economic transition and global change. Environmental Science & Policy, 13(7), 620-636.

Shahgedanova, M., Nosenko, G., Khromova, T., Muraveyev,A. (2010). Glacier shrinkage and climatic change in the Russian Altai from the mid-20th century: an assessment using remote sensing and PRECIS regional climate model. Journal of Geophysical Research: Atmospheres, 115, D16107, https://doi.org/10.1029/ 2009JD012976

Shahgedanova, M., Stokes, C. R., Gurney, S. D., Popovnin, V. (2005). Interactions between mass balance, atmospheric circulation, and recent climate change on the Djankuat Glacier, Caucasus Mountains, Russia. Journal of Geophysical Research: Atmospheres, 110(D4).

Sillmann, J., Kharin, V. V., Zwiers, F. W., Zhang, X., Bronaugh, D. (2013). Climate extremes indices in the CMIP5 multimodel ensemble: Part 2. Future climate projections, J. Geophys. Res. Atmos., 118, 2473–2493, https://doi.org/ 10.1002/jgrd.50188

Sorg, A., Bolch, T., Stoffel, M., Solomina, O., & Beniston, M. (2012). Climate change impacts on glaciers and runoff in Tien Shan (Central Asia). Nature Climate Change, 2(10), 725.

Surazakov, A. B., Aizen, V. B., Aizen, E. M., & Nikitin, S. A. (2007). Glacier changes in the Siberian Altai Mountains, Ob river basin (1952–2006) estimated with high resolution imagery. Environmental Research Letters, 2(4), 045017.

Tielidze, L. (2017). Glaciers of Georgia. Cham, Switzerland: Springer International Publishing. http://doi.org/10.1007/978-3-319-50571-8

Unger-Shayesteh, K., Vorogushyn, S., Farinotti, D., Gafurov, A., Duethmann, D., Mandychev, A., & Merz, B. (2013). What do we know about past changes in the water cycle of Central Asian headwaters? A review. Global and Planetary Change, 110, 4-25.

World Bank (2015) The Role of Glaciers in the Hydrologic Regime of the Amu Darya and Syr Darya Basins. The World Bank, Washington DC.

WGMS (2018) Fluctuations of Glaciers Database. World Glacier Monitoring Service, Zurich, Switzerland. https://DOI.org10.5904/wgms-fog-2018-06

Zhang, H., Ouyang, Z., Zheng, H. (2009). Journal Mountain Science 6: 255. https://doi.org/10.1007/s11629-009-0236-y

Zhou, H., Aizen, E., Aizen, V. (2017). Seasonal snow cover regime and historical change in Central Asia from 1986 to 2008. Global and Planetary Change, 148, 192-216.